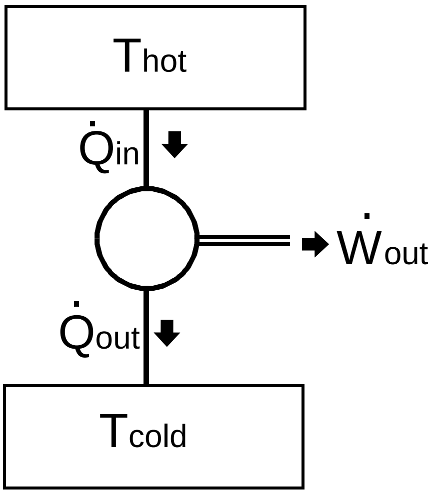
REFRIGERATION (& HEAT PUMPS)

Refrigeration is the 'artificial' extraction of heat from a substance in order to lower its temperature to below that of its surroundings. Primarily, heat is extracted from fluids such as air and many liquids, but ultimately from any substance.

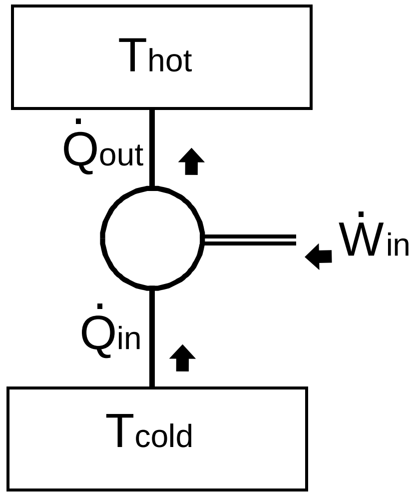
In order to extract heat a region of 'cold' has to be created. A number of effects can be used:-

- the Peltier effect (reverse of thermocouples);
- endothermic chemical reactions;
- induced vaporisation of a liquid.

In thermodynamic terms a refrigerator is a reversed heat engine. ie heat may transferred from a cold reservoir to a hot reservoir by expending work.



HEAT ENGINE



REVERSED HEAT ENGINE
(REFRIGERATOR)

A **Heat Pump** is no different in principle from a refrigerator apart from its pupose:
A heat pump is used to provide 'heat' whereas a refrigerator is used to obtain 'cold'.

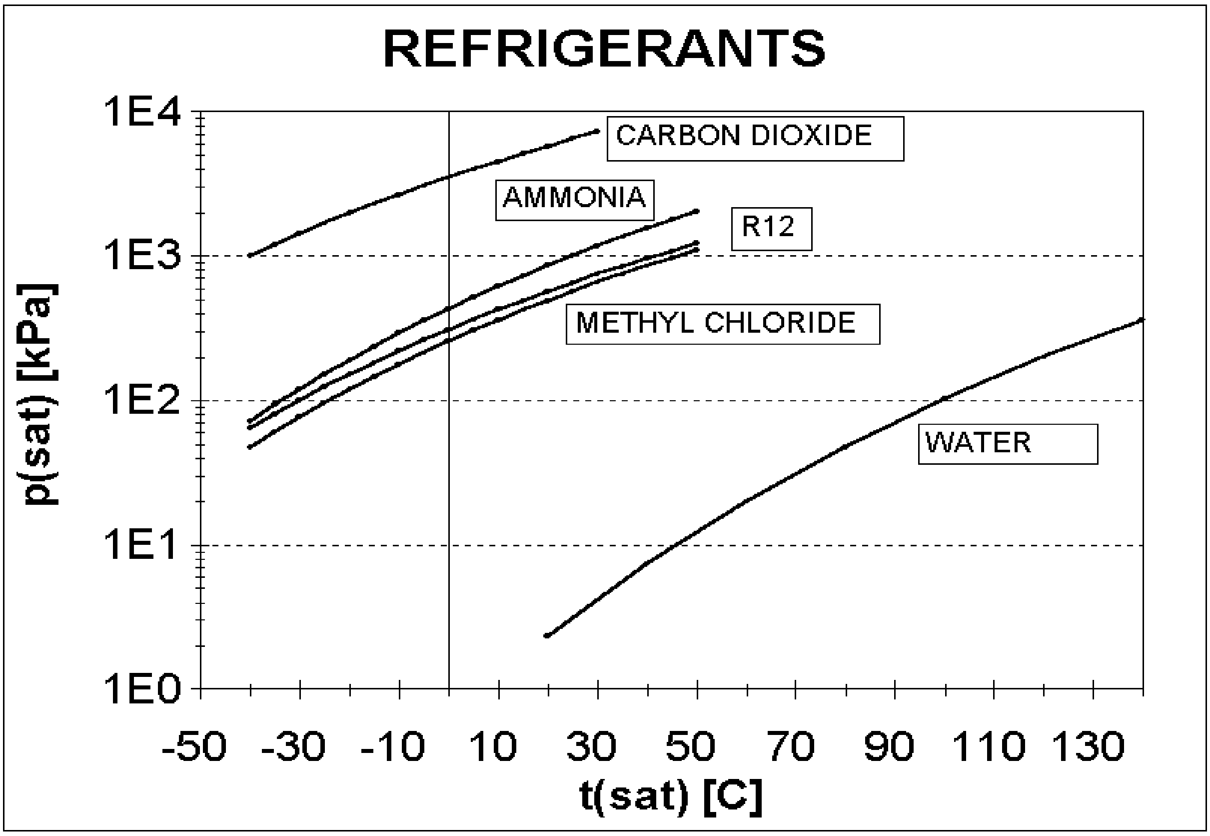
VAPOUR COMPRESSION REFRIGERATION

The above is somewhat of a misnomer, it would be more accurately described as 'vapour *suction* refrigeration'.
(Vapour compression is used to *reclaim* the refrigerant and is more aptly applied to Heat Pumps.)

Vapour compression refrigeration exploits the fact that the boiling temperature of a liquid is intimately tied to its pressure.
Generally, when the pressure on a liquid is raised its boiling (and condensing) temperature rises, and vice-versa.

This is known as the saturation pressure-temperature relationship. For H_2O, we investigated it using a Marcet boiler (for pressures above atmospheric).

We could repeat it for other substances, and at sub-atmospheric pressures:



Refrigerant properties

Ideally, a refrigerant will :

* be non-toxic - for health and safety reasons

*be non-flammable - to avoid risks of fire or explosion

* operate at modest positive pressures - to minimise pipe and component weights (for strength) and avoid air leakage into the system

* have a high vapour density - keeps the compressor capacity to a minimum and pipe diameters relatively small

* be easily transportable - because refrigerants are normally gases at SSL conditions they are stored in pressurised containers

* be environmentally friendly - non-polluting & non-detrimental to the atmosphere, water or ground

* be easily re-cycleable

* relatively inexpensive to produce

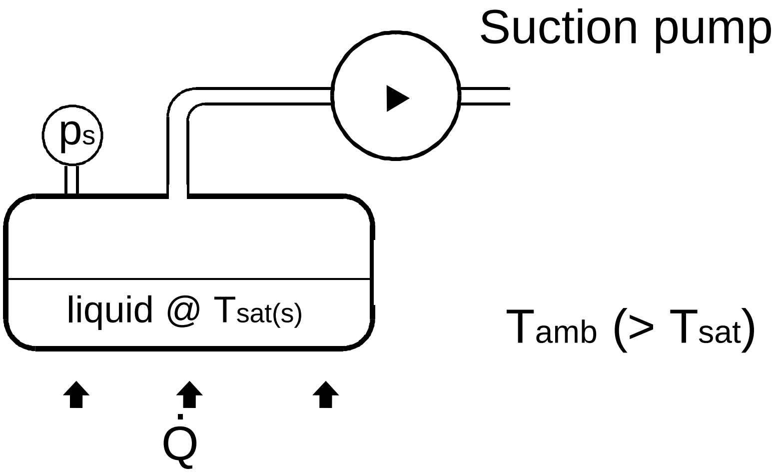
* compatible with the materials of the refrigeration system - non-corrosive, miscible with oil, chemically benign.

In practice the choice of a refrigerant is a compromise.

e.g. Ammonia is good but toxic and flammable;

R12 very good but detrimental to the Ozone layer

Refrigeration:-



The pressure (p_s) is a function of how rapidly we remove the vapour (how hard we suck) and how quickly the vapour is formed.

At *equilibrium* the rate at which vapour is formed (determined by $\dot{Q}$) equals the rate at which it is removed.
Therefore **both** the heat transfer rate into the liquid ($\dot{Q}$) **and** the vapour removal rate (suction pump capacity) determines the pressure and hence $T_{sat(s)}$.

$$\dot{Q} = \dot{m}\, h_{fg}$$

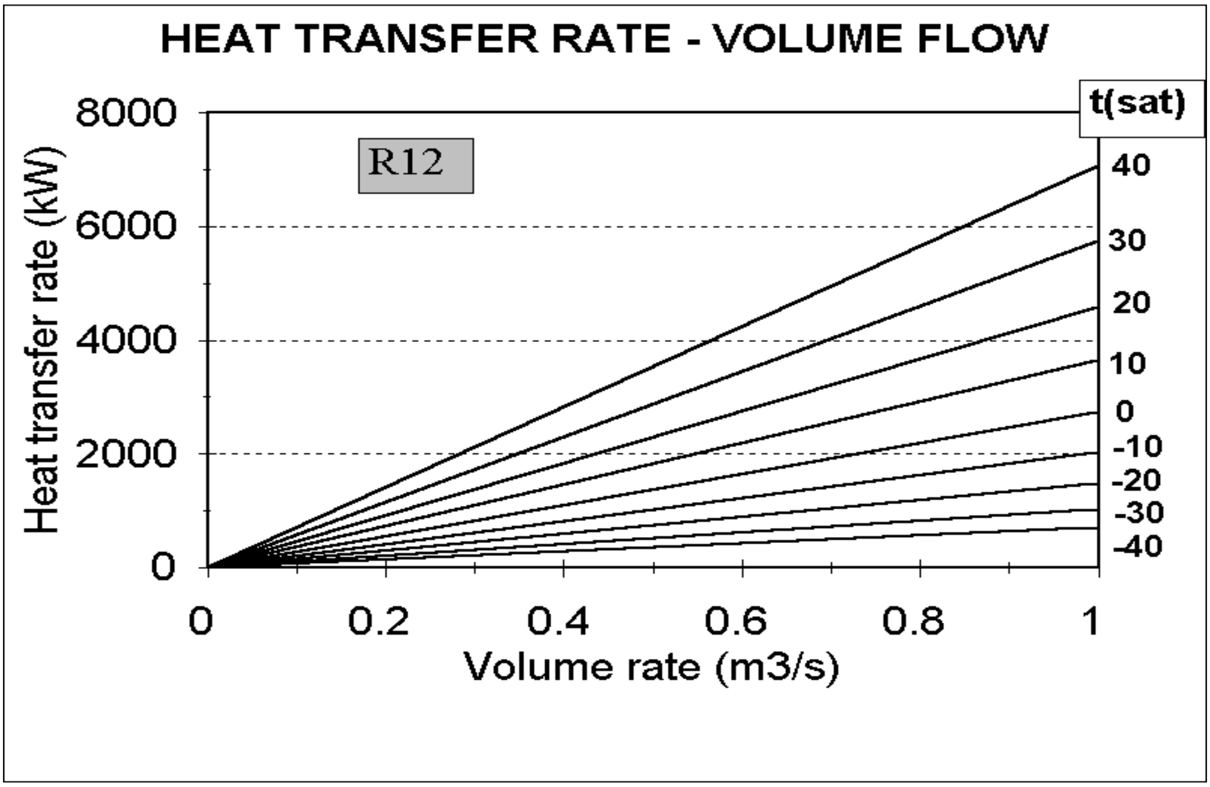
$$\dot{m} = \rho_g \dot{V}$$

$$\therefore \qquad \dot{Q} = \rho_g \dot{V} h_{fg}$$

or

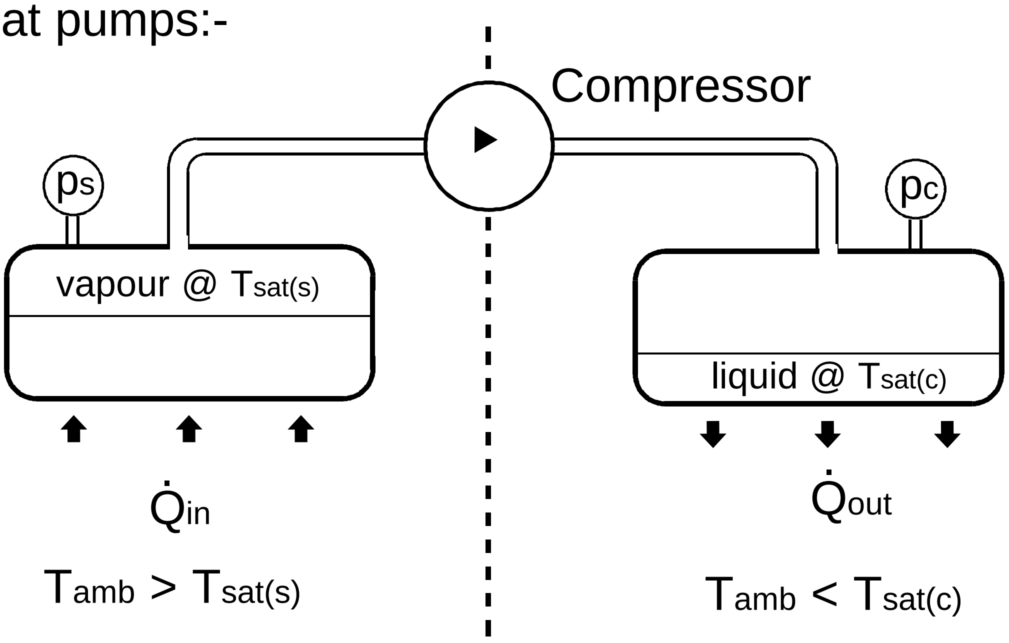
$$\boxed{\dot{Q} = \frac{\dot{V} h_{fg}}{v_g}}$$

Note that both h_{fg} and v_g depend on the saturation temperature (or pressure).



Obviously, the above system would eventually run out of liquid and the refrigerating effect would cease.

Heat pumps:-



The RHS of the above system is the 'converse' of the LHS, and constitutes a Heat Pump.
Heat is 'pumped' from the LHS to the RHS.

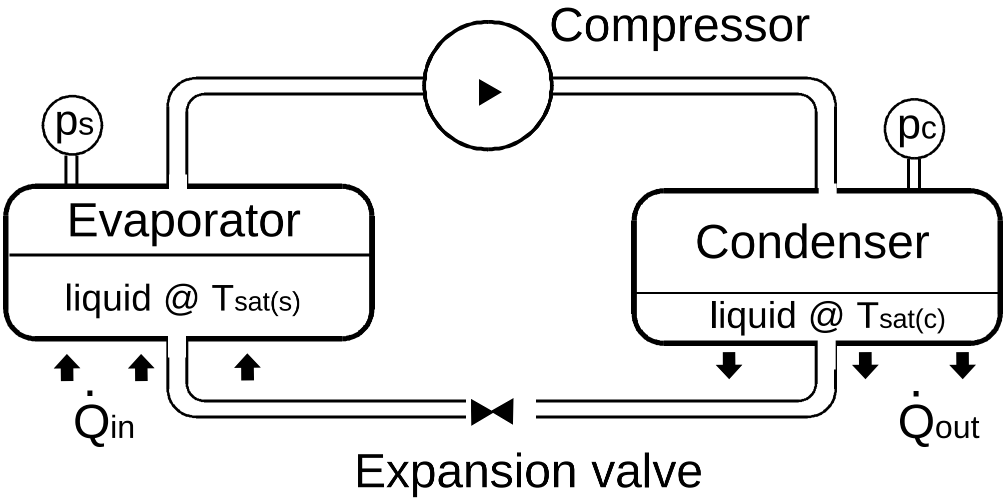
The main difference is that the vapour, after compression, will almost certainly be superheated and must cool to $T_{sat(c)}$ before condensing will occur.

The same reasoning (in converse) applies to the RHS as previously applied to LHS.

Note:
p_c = Condenser or 'high side' pressure
p_s = Evaporator, 'low side', or suction pressure.

Obviously, with the above system, all the refrigerant would eventually end up on the RHS, and the heat pumping (& refrigeration) effect would cease.

Clearly, to ensure that the system can operate continuously liquid refrigerant needs to be fed from the RHS back to the LHS.
This can be achieved by simply allowing it to flow back under its natural pressure difference.



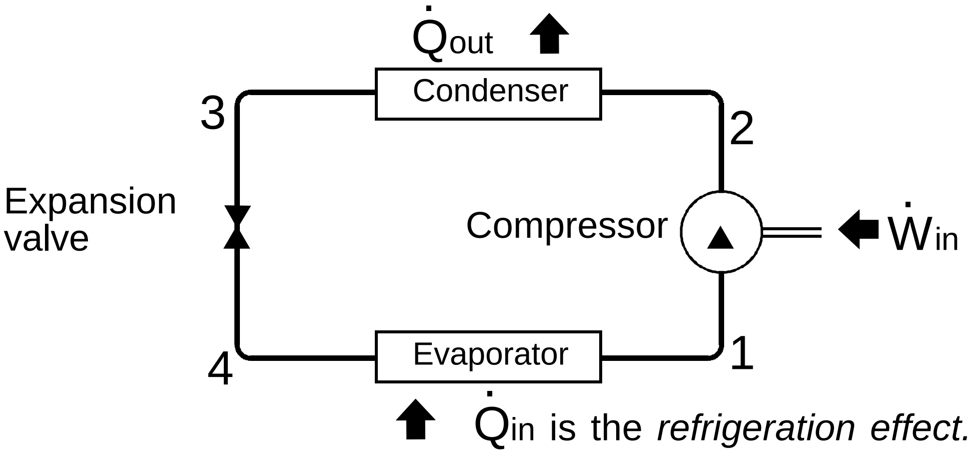
In this way a continuous closed circuit refrigeration (or heat pump) system is obtained.

Note:

Control of the liquid flow rate is needed to ensure that it equals the vapour formation rate, and an appropriate balance of liquid quantities in the evaporator and condenser is maintained;

When the liquid passes through the expansion valve it experiences a sudden drop in pressure which causes instantaneous boiling (known as flashing). Vapour is formed using the liquid's sensible heat which causes the liquid to drop in temperature to $T_{sat(s)}$. A saturated liquid/vapour mixture will enter the evaporator.

Simplified refrigeration system diagram:



$\dot{Q}_{in}$ is the *refrigeration effect.*

We may analyse the whole system or individual components:

System performance:

$$\dot{Q}_{out} - \dot{Q}_{in} = \dot{W}_{in}$$

For operation as a **refrigerator**, a measure of system performance is the amount of heat ***absorbed*** per unit work supplied to drive the system.
This is known as the Coefficient of Performance (ref.)

$$\boxed{COP_{ref} = \frac{\dot{Q}_{in}}{\dot{W}_{in}}}$$

For operation as a **heat pump,** a measure of system performance is the amount of heat ***delivered*** per unit work supplied to drive the system.
This is known as the Coefficient of Performance (hp.)

$$\boxed{COP_{hp} = \frac{\dot{Q}_{out}}{\dot{W}_{in}}}$$

It follows that (for the same system)

$$COP_{hp} = COP_{ref} + 1$$

The SFEE may be applied to each of the components:-

We shall assume that KE & PE effects are negligible, ie the SSFEE is applicable; viz

$$\dot{Q} + \dot{W} = \dot{m}\,\Delta h$$

Compressor:

Compression assumed adiabatic: $\therefore\ \dot{Q} = 0$

$$\dot{W}_{12} = \dot{m}\,(h_2 - h_1)$$

or $$\boxed{\dot{W}_{in} = \dot{m}\,(h_2 - h_1)}$$

Condenser:

$$\dot{W}_{23} = 0$$

$$\therefore\ \boxed{\dot{Q}_{out} = \dot{m}\,(h_2 - h_3)}$$

Expansion valve:

$$\dot{W}_{34} = 0 \quad \& \quad \dot{Q}_{34} = 0$$

$$\therefore \boxed{h_3 = h_4}$$

Evaporator:

$$\dot{W}_{41} = 0$$

$$\therefore\ \boxed{\dot{Q}_{in} = \dot{m}\,(h_1 - h_4)}$$ refrigeration effect

It follows that :

$$COP_{ref} = \frac{h_1 - h_3}{h_2 - h_1}$$

$$COP_{hp} = \frac{h_2 - h_3}{h_2 - h_1}$$

In order to determine the above we need to know the specific enthalpy values. Because refrigerants work in the liquid/vapour phases we must use appropriate property **charts or tables.**

Refrigerant properties (Charts and Tables)

Because refrigeration systems basically work between two pressures, and specific enthalpy is one of the most useful properties we need, refrigerant thermodynamic properties are normally presented in the form of a **pressure - specific enthalpy** (or p-h) chart.

This is done for convenience, and is simply an alternative way of presenting property data.
Instead of (eg) p-V, or T-s, or h-s.

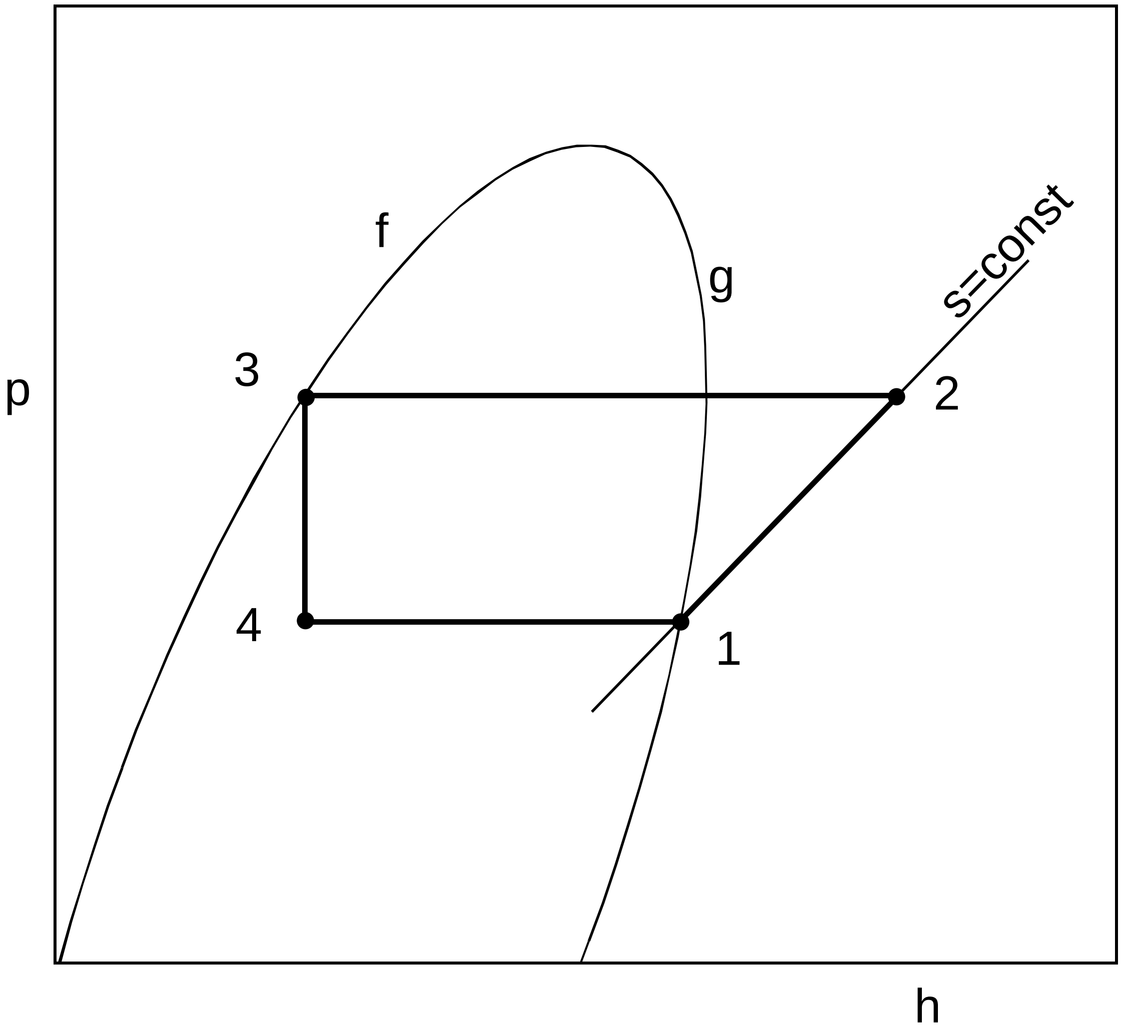
Other useful properties are also shown on the chart, viz: specific entropy, specific volume, temperature and quality. Regard these properties as ‘contours’.

Note:
The pressure axis (y-axis) is typically logarithmic.

THE IDEAL REFRIGERATION CYCLE

- isentropic compression (1 → 2)
- constant pressure cooling/condensation (2 → 3)
- throttling (3 → 4)
- constant pressure vaporisation/heating (4 → 1)

The ideal refrigeration cycle plotted on the p-h chart:

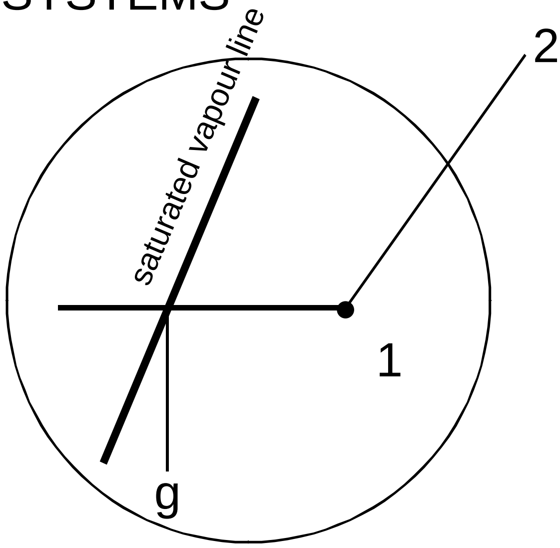


REAL REFRIGERATION SYSTEMS

Evaporator superheat:

g → 1

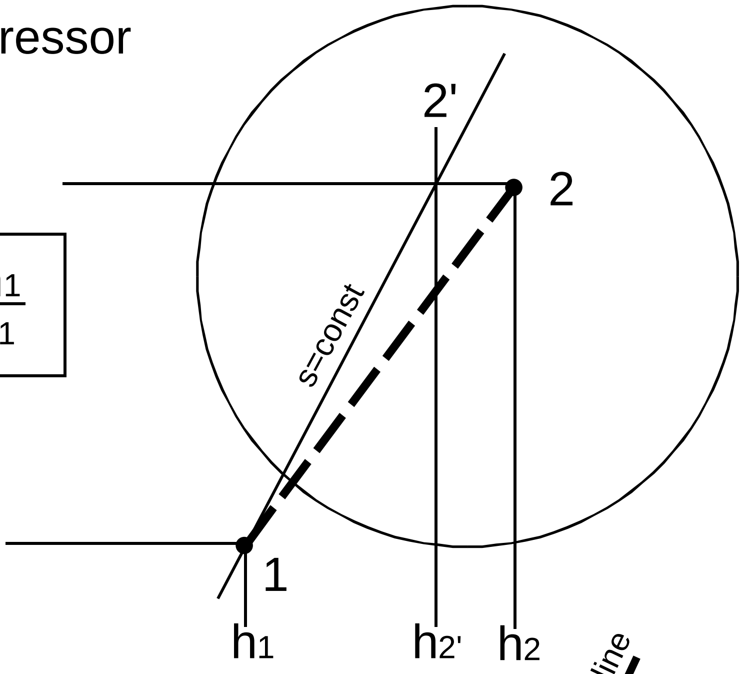
given in K
above $T_{sat(s)}$



Isentropic Compressor Efficiency:

$$\boxed{\eta_{isen} = \frac{h_{2'} - h_1}{h_2 - h_1}}$$

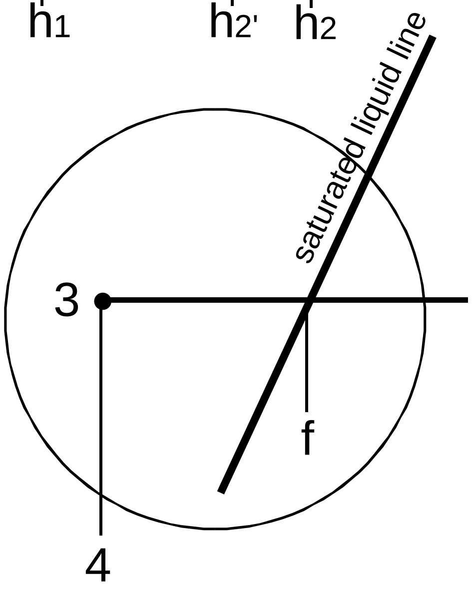
NB: $s_1 = s_{2'}$



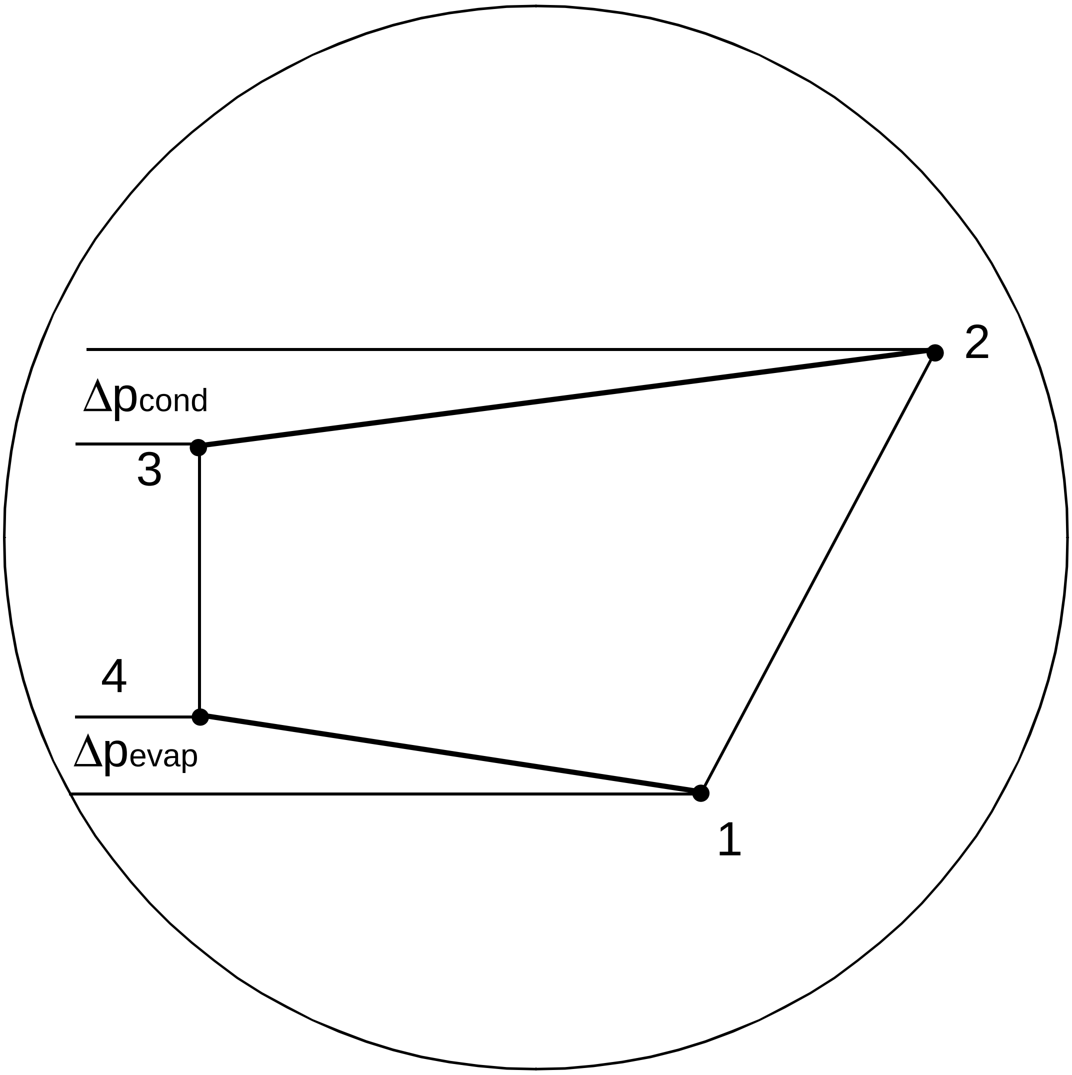
Condenser sub-cooling:

f → 3

given in K
below $T_{sat(c)}$



Pressure drops in evaporator and condenser:

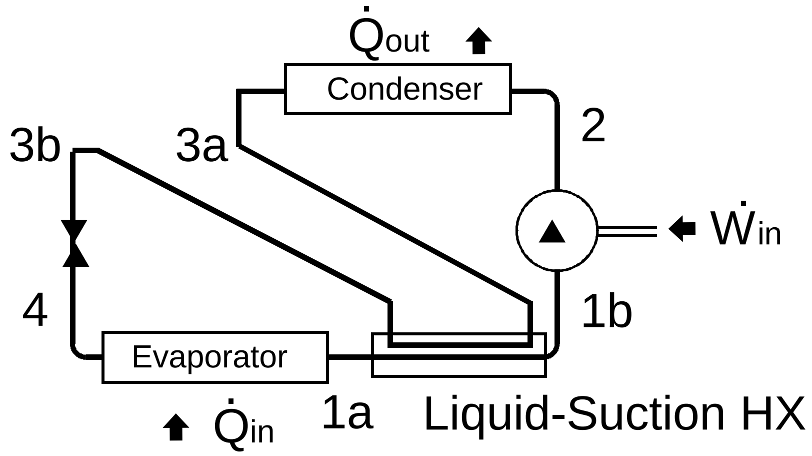


(Shown exaggerated !)

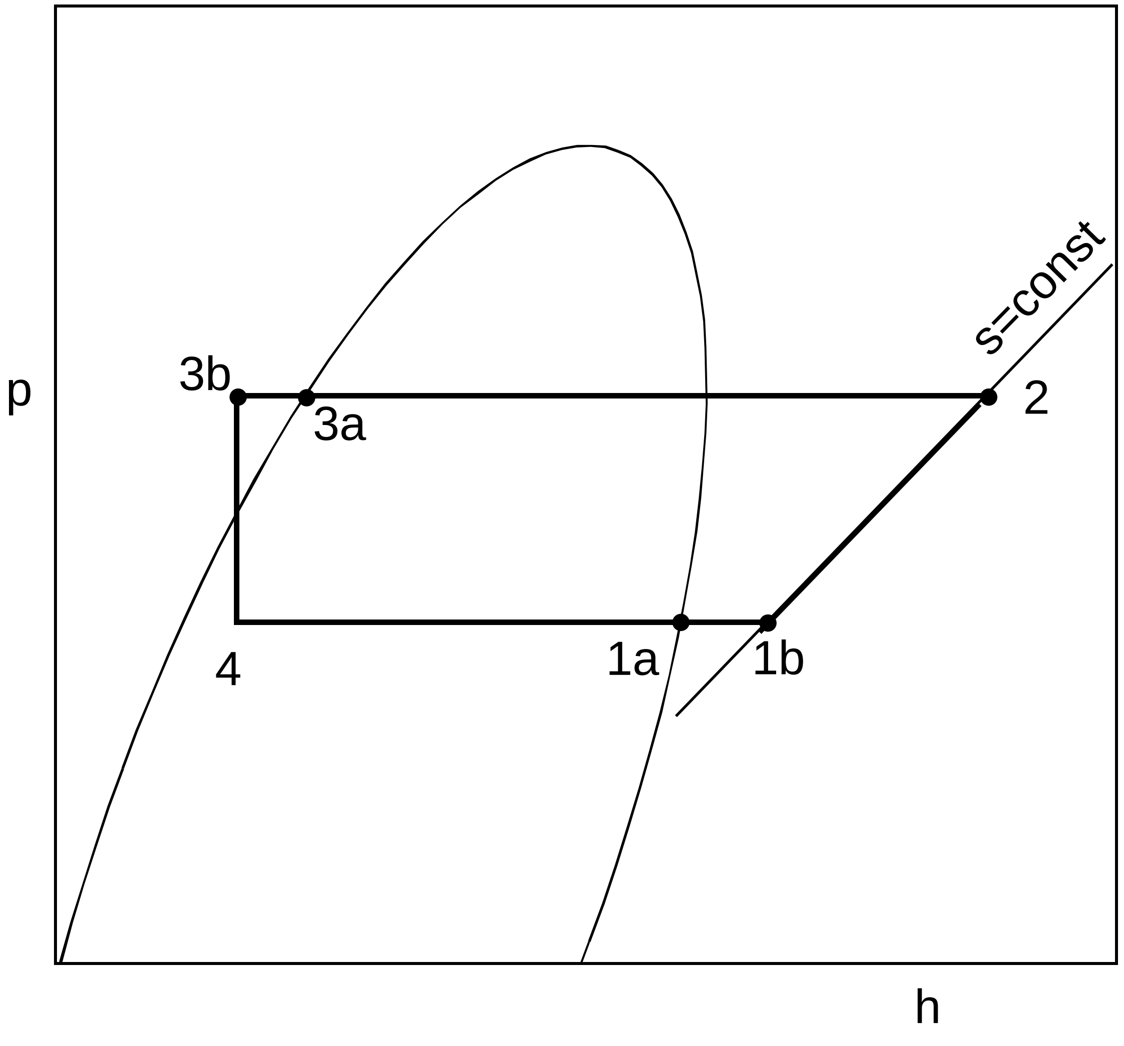
Clearly, any or all of the above effects can be present, but the pressure drops are often small enough to be neglected.

REFRIGERATION SYSTEM PERFORMANCE IMPROVEMENT

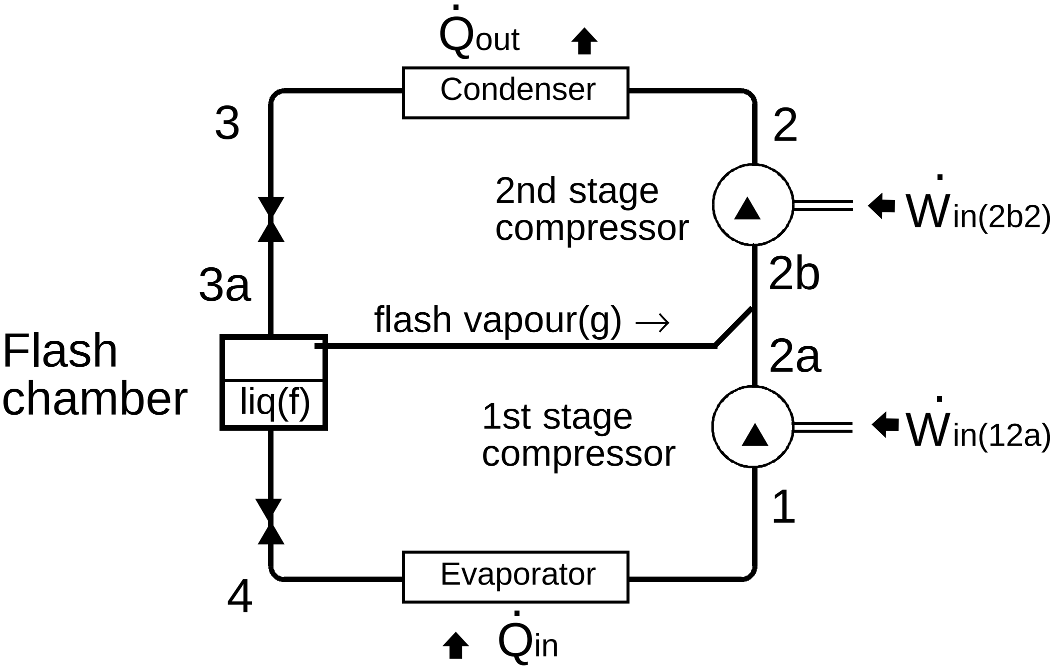
Liquid-Suction heat exchanger:

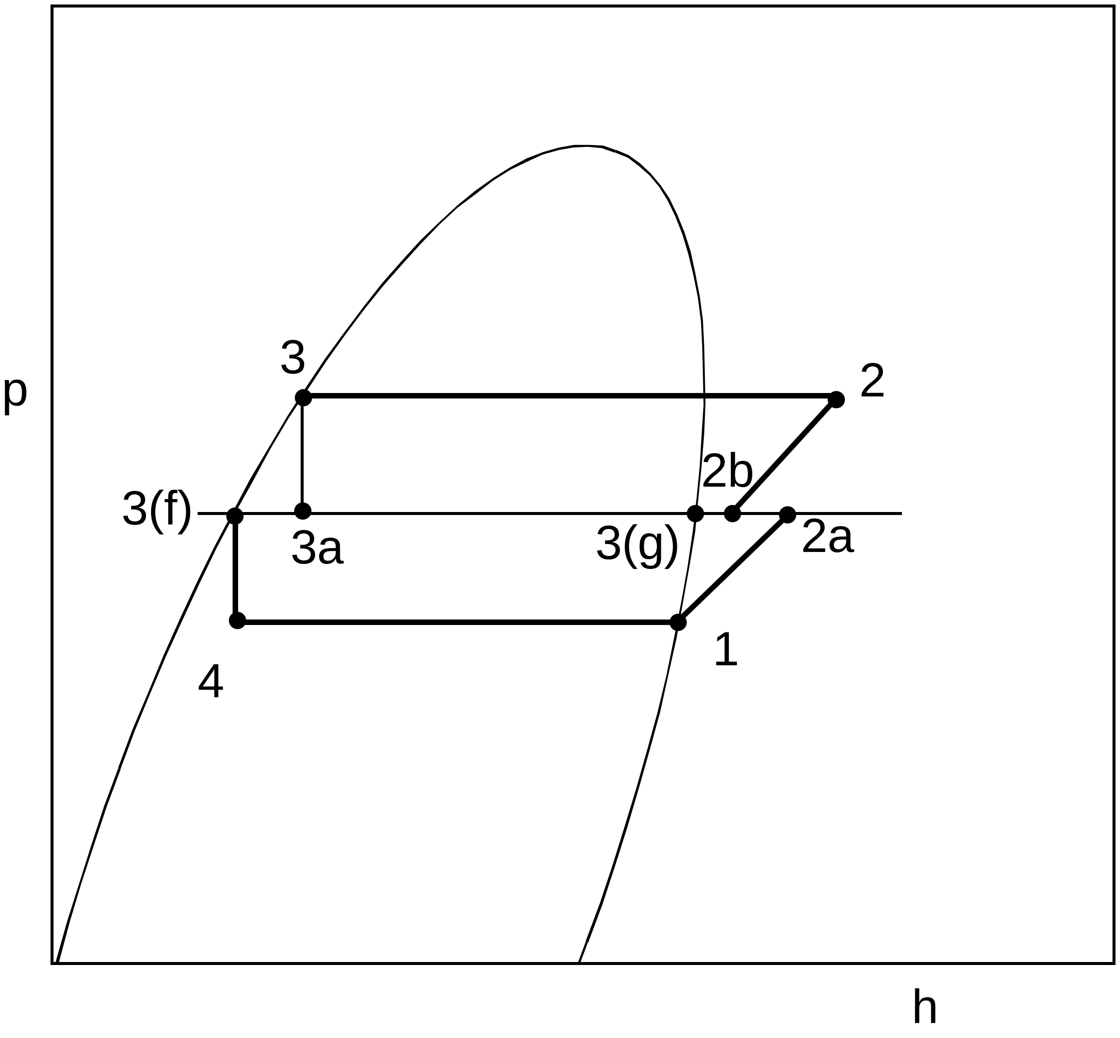


Assuming no losses : $h_{1b} - h_{1a} = h_{3a} - h_{3b}$



Multiple compression using flash chamber(s):





At point 3a we have a mixture of vapour and liquid which is separated in the flash chamber.

The proportion of the total mass flow which is ***liquid*** (and proceeds to the evaporator) is given by:

$$x_f = \frac{h_{3(g)} - h_3}{h_{3(g)} - h_{3(f)}}$$

The remaining vapour mixes with the discharge from the first stage compressor to give different inlet conditions to the second stage.

Assuming adiabatic mixing:

$$x_f h_{2a} + (1 - x_f) h_{3(g)} = 1 \times h_{2b}$$

A similar equation can be used to find s_{2b}

Finally the COP is given by:

$$COP = \frac{x_f (h_1 - h_4)}{x_f (h_{2a} - h_1) + (h_2 - h_{2b})}$$